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# VARIABILITY IN COMPONENT LIFE DUE TO FATIGUE CRACK GROWTH VARIABILITY (PREPRINT)

**A.H. Rosenberger**

**Metals Branch**
**Metals, Ceramics, and NDE Division**

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**14. ABSTRACT**
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**Variability in Component Life due to Fatigue Crack Growth Variability**

A. H. Rosenberger

Air Force Research Laboratory, Materials and Manufacturing Directorate,

AFRL/RXLMN, Wright-Patterson AFB, OH  45433-7817

**Abstract**

The variation in component damage tolerance life is assessed in terms of the variation in crack growth rate using a cycle by cycle integration technique.  The results of a fatigue crack growth rate interlaboratory study are reanalyzed in order to predict the life of a component-like structure.  It was determined that the variability in crack growth rate is fundamentally the same as the variability in the predicted fracture mechanics life for 4130 steel, and the aluminum alloys 2024-T351 and 7075-T6.  Though only a limited K range able to be examined, it appears that the match of the variability of crack growth rate and component life is relatively independent of the range of K used in the comparison.

**Introduction**

The US Air Force requires a damage tolerance assessment for all airframes and engines [1,2] to set the inspection windows for safe operation.  Traditionally the crack growth life is assumed to be a relatively well behaved material property as reaffirmed by a recent round robin by ASTM [3] to reassess the variability in crack growth rate data as generated using ASTM standard E647 [4] by modern test systems using, largely, automated crack measurement techniques, i.e., compliance and electrical potential difference.  Three materials; 4130 steel (normalized + heat treated), 7075-T6, and 2024-T351 were tested under conditions and forms as shown in Table 1. A total of 141 specimens were tested by 18 laboratories. The crack growth rate was determined at set $\Delta K$ points (Log $\Delta K$ increments of 0.1 where K is in units of Log[ Ksi$\sqrt{}$in])  by interpolating the surrounding data points.  The variability in crack growth rate was characterized by 2 standard deviations of the data.  More details of the analysis can be found in reference [3]. It was found that the crack growth rates varied by 1.9x for the 4130 steel and 2.4x for the aluminum alloys (2.3x for 2024-T351 and 2.6x for 7075-T6 ).  Surprisingly, there was not much difference in crack growth variability between the current and previous assessment [5], circa 1975, that is used in the precision and bias statement for ASTM standard E647 [4].

The goal of the current study is to assess relationship between the crack growth rate variability and the variability of the damage tolerant life of a component. One could argue that the scatter in component life may be less than the scatter in crack growth rate as individual cracks *may* have periods of enhanced and retarded crack advance as the crack passes various microstructural features. This would be measured as scatter in the crack growth rate, but could average out the overall crack growth rate to produce a more uniform component life. The data set from the new ASTM round robin is available [6] for further study and is an ideal choice to assess the influence of fatigue crack growth variation on component life. The following section will describe the methodology to use the ASTM round robin results in a simple component life assessment. This will be compared to the scatter in crack growth rate and compared to other, single laboratory, studies of crack growth variability.

**Life Analysis Methods**

The crack growth data from the ASTM round robin was assessed to determine the maximum number of samples that could be used for this study having a relatively broad K-range overlap. It was determined that there was limited overlap in the crack growth rate results. In several instances some samples or laboratories stopped tests at $\Delta K$ levels lower than those where other samples or laboratories. In the round robin, 141 samples were tested by 18 laboratories but only 78 samples from a total of 13 laboratories were used in the present analysis. Table 2 shows the laboratories and number of samples per laboratory used in this study compared to the total ASTM data set. Also shown in Table 2 is the $\Delta K$ range that was used in the life calculations. That is, the highest minimum and lowest maximum $\Delta K$ reported for the group of selected specimens. The samples that were not used would have required a narrower $\Delta K$ range for the life calculations which would have substantially reduced the level of crack growth that could be examined. In general, at least an order of magnitude in crack growth rate was desired for the comparison. Several laboratories were dropped from all analysis as they consistently captured data at only very low delta K levels. It should be noted that generally half of the ASTM round robin results were used for each material condition and there was no condition having less than ten crack growth curves. Plots of crack growth rate versus delta K are shown in Figure 1, (A) – (F) for all of the data sets used in this analysis. The limits of delta K used for the comparison is also shown in the plots. One point to note is the “outlier” crack growth curve from laboratory O, specimen O(W2-2-22) in figure 1(D) for the ALX-C condition which was also identified in the report [3] as being an outlier. No error in testing was found that could be used to eliminate it from the analysis and it may represent the extreme in the crack growth variability for the study. However, the fact that the intralaboratory variability for this test condition and laboratory was significantly greater than all other laboratories was reason to censor that data, both specimens O(W2-2-21) and O(W2-2-21), in both the original ASTM study and this work. Figure 1 shows that in all cases, the present analysis covers over an order of magnitude in crack growth rate, largely in the Paris region.

The variability in crack growth rate was quantified by McKeighan, et al. [3] as the ratio, in log space, as the ratio of average growth rate +2*standard deviation to the average growth rate – 2* standard deviation for each K examined. For a given material and test condition, variability was characterized as the average of these individual K levels. Since the current study uses only some of the samples and assesses the cumulative crack growth for a limited $\Delta$K range, the variability was recalculated based on the tabulated K level results in reference 6. It was not possible to go all the way down to the individual sample level to get the *exact* variability for comparison. Since the current study used approximately half of the samples as the original study, the variability may be slightly less in the present study, but it Is not thought to be appreciable. Table 3 shows details of the average crack growth variability for the six individual test conditions for both the full range of test data and for the more limited K range in the current study. The average crack growth rate variability for the limited K-range

As the goal of the study was to assess how the crack growth rate variability affected the variability in a components damage tolerant life, the curves were not fit [8] but life was calculated by numerically growing the crack from an initial to final size using the actual da/dN vs. $\Delta$K data. A fortran code was used that fit a power law between adjacent crack growth rate points and advanced the crack cycle by cycle and output the crack extension at intervals of 100 cycles. The stress intensity factor information is input to the program in terms of an *a* versus $\Delta$K table for the geometry and loading of interest.

The component chosen for the life assessment was a uniformly loaded plate, 2 mm thick and 200 mm wide having a circular hole of 5 mm located at the center of the plate. This is essentially a M(T) specimen, but the hole is larger and there is some notch influence at shorter crack lengths. The $\Delta$K versus *a* relationship was determined using a *classic* AFGrow [7] solution for a single thru crack at a hole, shown in Figure 2. This $\Delta$K vs. a was then used in the previously described fortran code to predict the crack extension for the component.

## Component Life Results and Discussion

There is some artificially in calling the results "component life" since the life integration is neither starting from a very small size ( the NDE limit) nor growing to a critical crack length ($K_{IC}$ or $K_Q$) – the crack growth rate data would not allow this. However, for a given material condition, the cracks are all grown from the same initial size to the same final size. So it should be valid to compare the variability in the number of cycles to propagate the crack over a given, wide level of crack extension to the variability in measured crack growth rate over that same interval in K space. To simplify the analysis, all "components" were cycled with the same stress range of 50 MPa. Using this value, the initial and final crack lengths were determined using the $\Delta K$ vs. a relationship in Figure 2. The resultant crack length versus cycles is shown in figure 3 (A-F) for the six test conditions and materials. Examination of these curves shows the traditional shape of the a vs. N curve with fanning as the crack extends. Apparent are changes in the slope that represent the variation in the growth rate data from [3] and the crack growth curves often cross which would also be expected based on the crack growth rate curves. (Remember that the crack growth curves from laboratory O for the ALX-C test condition, the shortest and longest life in figure 3(D), were not used in characterizing the crack growth rate variability or the cumulative crack extension.

A comparison of the average fatigue crack growth rate variability and the total component life variability is shown in Figure 4 for the six different materials / test conditions. In all cases, the life variability is lower than the average crack growth rate variability, but not substantially lower. The biggest difference between the life and rate data is in the ALX-C condition which only has 9 of the original 20 data sets once the data from laboratory O was censored. This may indicate that the number of crack growth rate curves used in the life prediction is missing some of the larger, true variability for that material (2024-T351) or test condition (R = 0.5, 6.35mm thick C(T) specimen). The number of specimens used for the STL-A (4130 steel, R=0.1, 6.35mm thick C(T) specimen) to calculate the crack growth rate variability was 13 out of 28, yet the variability in *life* and *growth rate* compare favorably. One issue that could color the comparison is that the limitation in the $\Delta K$ ranges is not consistent between the materials or test conditions. To address this influence, a comparison was made for the life variability for the six test conditions at different levels of total crack extension. Figure 5 shows the life variability for different fractions of the growth range – from 25% to the full usable range (shown in Table 2). It can be seen that the shorter the increment of growth, the larger the resultant life scatter. This is generally caused by the faster decrease in average life as the standard deviation decreases more slowly. Clearly under very short increments of crack extension (life), the variability can be much greater (ALX-A has the nearly ½ of the life of the next shortest material / test condition). The largest increase in life variability is ALX-A but the majority of the increase is caused by one specimen, J(W2-2-14). This specimen clearly has higher growth rate at the lower bound of the da/dN vs. $\Delta K$ curve, Figure 3(C) and censoring this sample would reduce the variability to 3.47. Note also that this curve merges with the cloud of data at a $\Delta K$ of less than 6 MPa$\sqrt{m}$ such that the scatter in life, using greater increments of crack extension, would be reduced.

Comparisons of the life scatter in fracture mechanics testing are usually conducted in a single laboratory [9-11] so the influence of conducting the data generation at several sources is not well understood. The well known work of Virkler, et al., [9] covered the crack growth variability in 2024-T6 aluminum in 2.54mm thick M(T) specimens at an R of 0.2. The total life scatter for a set of 68 identical specimens was 1.19 (average life of 2334573 cycles and a standard deviation of 10191 cycles). This variability is substantially less than that of the ALX-A (2.83) and ALX-B (1.76) 2024-T351 samples at an R of 0.1. The difference in scatter could be due to the number of laboratories included in the current study and the latitude that the ASTM Standard E647 (4) allows in the generation of the crack growth rate data. The ASTM Round Robin report (3) does explore the intralaboratory scatter and did find labs that individually had variations for ALX-A and ALX-B ad low as 1.18 and 1.11, respectively. It appears that the Virkler [9] data primarily has low scatter due to the generation in a single laboratory and an exacting, repeatable experimental technique. This study indicates that in the real world, the scatter will be higher. Ghonem and Dore (10) and Ghonem (11) examined the fatigue crack growth variability in replicate tests (60 for each condition) of 3.175 mm thick M(T) samples of 7075-T6 at stress ratios of 0.4, 0.5, and 0.6 at several force levels. Unfortunately references 10 and 11 did not report statistics of the life variation but the graphical data indicated scatter ranging from 2 to 4 based on the ratio of maximum cycles to failure over minimum cycles to failure. This is similar to the scatter for the R = 0.5 tests, ALX-C in 2024-T351 and the generally higher scatter in the thin 7075-T6 samples in data set ALN-A.

## Conclusions

The crack growth rate variability was converted to life variability for a simple component-like structure for six different loading and material combinations using cycle by cycle analysis of the crack growth rate data. In all cases the variation in crack growth rate, the combined acceleration and retardation, was *not* reduced when these curves were integrated to predict component life. The component life variation was found to be the same as the crack growth rate variation and was found to be relatively independent of the length of crack extension – above some minimum length. The predicted variation in crack growth life for 2024- and 7075-T6 aluminum alloys was found to be similar to the variation in experimentally determined life from different studies.

Overall, designers can use their understanding of growth rate variation as a means to assess component life variation for damage tolerance applications. This appears to be applicable for structures that follow linear elastic fracture mechanics.

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Table 1: Materials, specimen configuration, test conditions, and number of specimens tested in the ASTM crack growth rate variability round robin, after [3].

| Test Condition ID | Material | Specimen Type | Thickness (mm) | Stress Ratio (R) | Specimens Tested |
|---|---|---|---|---|---|
| STL-A | 4130 Steel | C(T) | 6.35 | 0.1 | 28 |
| STL-B | 4130 Steel | C(T) | 6.35 | 0.8 | 17 |
| ALX-A | Al 2024-T351 | C(T) | 6.35 | 0.1 | 29 |
| ALX-C | Al 2024-T351 | C(T) | 6.35 | 0.5 | 20 |
| ALX-B | Al 2024-T351 | M(T) | 9.53 | 0.1 | 23 |
| ALN-A | Al 7075-T6 | M(T) | 3.18 | 0.1 | 24 |

Table 2: Number of specimens used for each laboratory in reference [3] and this study and the $\Delta K$ range ($MPa\sqrt{m}$) that was used for the life calculation

| Lab ID | Number of Specimens for Each Test Condition (Ref [3] / this study) | | | | | |
|---|---|---|---|---|---|---|
| | STL-A | STL-B | ALX-A | ALX-C | ALX-B | ALN-A |
| A | 1/1 | 3/2 | 3/2 | | | |
| B | 2/2 | 2/2 | 2/2 | 2/2 | 2/2 | 2/2 |
| C | 2/2 | | 2/2 | 2/2 | | |
| D | | | | | 3/0 | 3/0 |
| E | 2/2 | | 2/2 | | 2/2 | 2/0 |
| F | 4/0 | 2/0 | 2/0 | 2/0 | 2/0 | 2/0 |
| G | 3/1 | 2/2 | 3/3 | 2/2 | 1/1 | 2/1 |
| H | 2/2 | | 2/2 | 2/1 | | |
| I | 2/0 | 2/0 | 2/0 | 2/0 | 2/0 | 2/1 |
| J | 2/0 | 2/1 | 3/2 | | | |
| K | 2/2 | | 2/0 | 2/0 | | |
| L | | | 2/2 | 2/2 | 3/3 | 3/3 |
| M | | | | | 3/1 | 3/3 |
| N | 2/0 | 2/1 | | | | |
| O | 2/0 | | 2/1 | 2/2 | | |
| P | 2/1 | 2/2 | 2/2 | 2/0 | 2/1 | 2/2 |
| Q | | | | | 2/2 | |
| R | | | | | 1/0 | 3/0 |
| SUM | 28/13 | 17/10 | 29/20 | 20/11 | 23/12 | 24/12 |
| $\Delta K$ range | 12.92 to 51.57 | 9.06 to 25.11 | 7.88 to 29.17 | 6.74 to 20.36 | 6.60 to 22.39 | 7.04 to 24.38 |

Table 3: Average variability in crack growth rate for the six test conditions, from [3]

| Test Condition ID | Crack Growth Variability (Full K Range) | Crack Growth Variability (Limited K Range) |
|---|---|---|
| STL-A | 1.94 | 1.84 |
| STL-B | 1.90 | 1.72 |
| ALX-A | 2.63 | 2.83 |
| ALX-C | 2.43 | 2.68 |
| ALX-B | 1.84 | 1.76 |
| ALN-A | 2.56 | 3.30 |

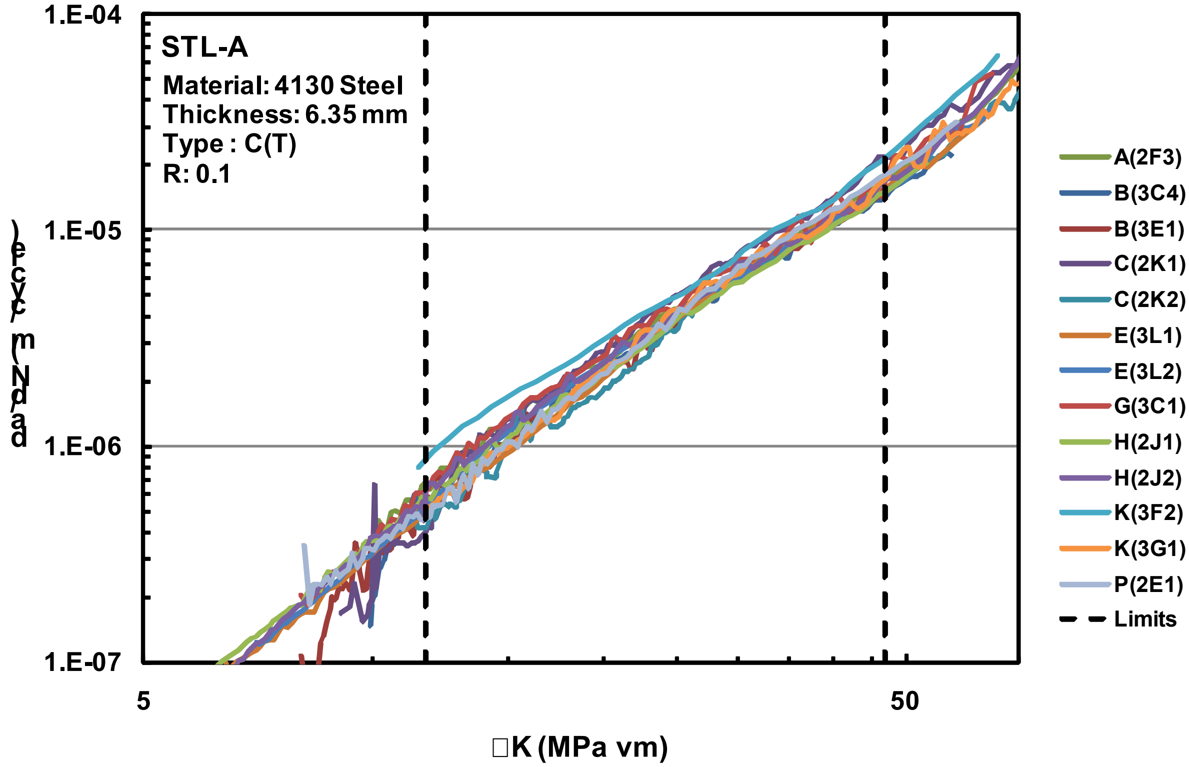


Figure 1: Crack growth rate versus ΔK: (A) STL-A, 4130 steel, 6.35 mm thick, C(T) specimen, stress ratio 0.1.

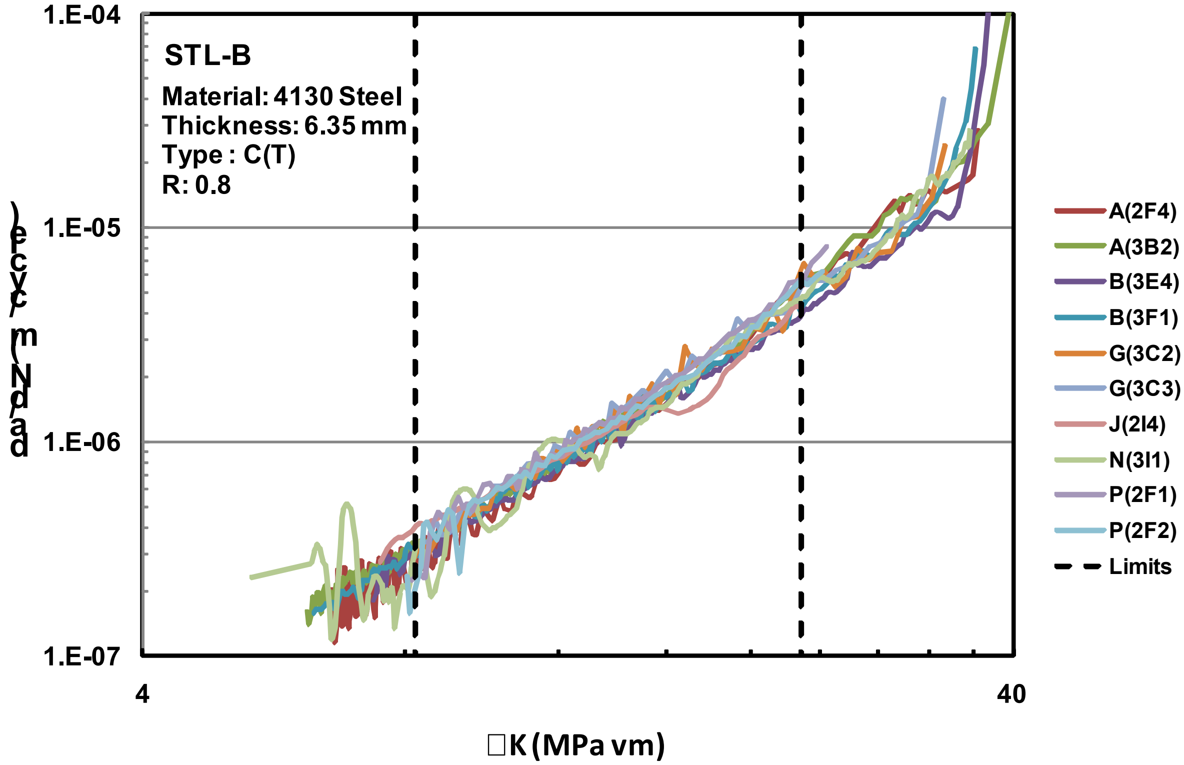


Figure 1: Crack growth rate versus ΔK: (B) SLT-B, 4130 steel, 6.35 mm thick, C(T) specimen, stress ratio 0.8.

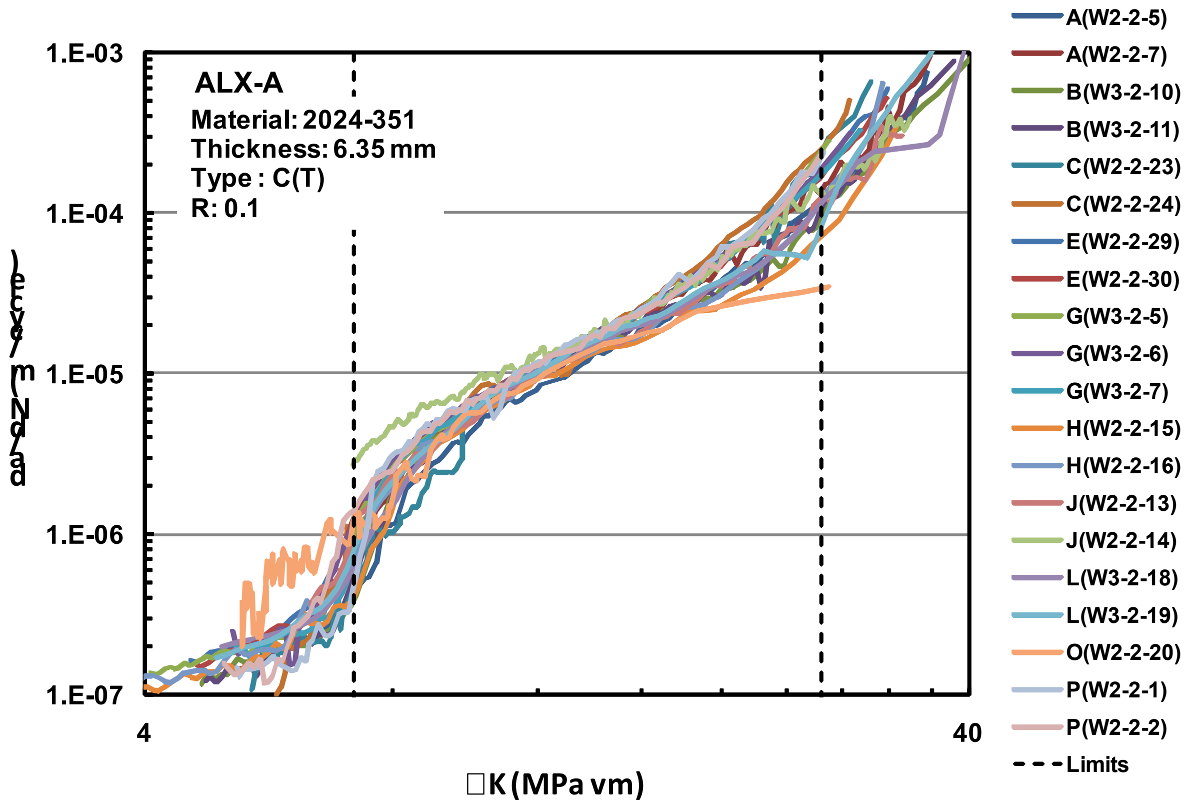


Figure 1: Crack growth rate versus ∆K: (C) ALX-A, 2024-T351, 6.35 mm thick, C(T) specimen, stress ratio 0.1.

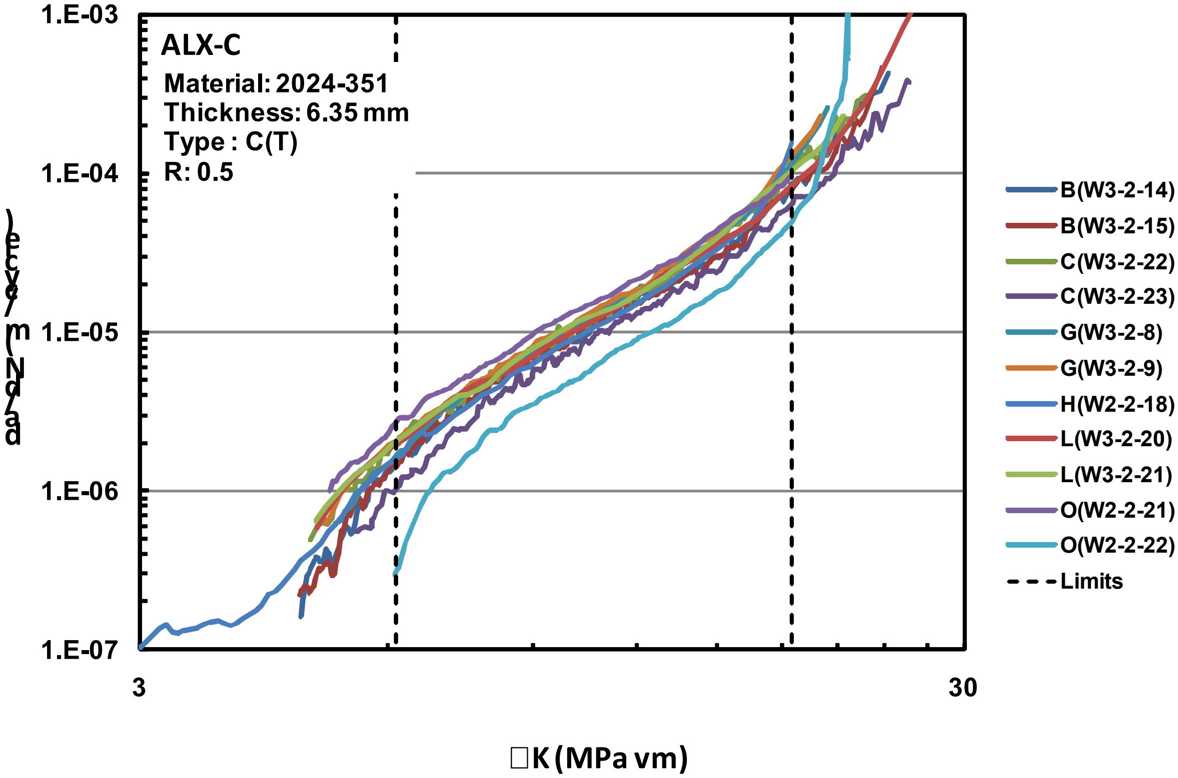


Figure 1: Crack growth rate versus ΔK: (D) AXL-C, 2024-T351, 6.35 mm thick, C(T) specimen, stress ratio 0.5.

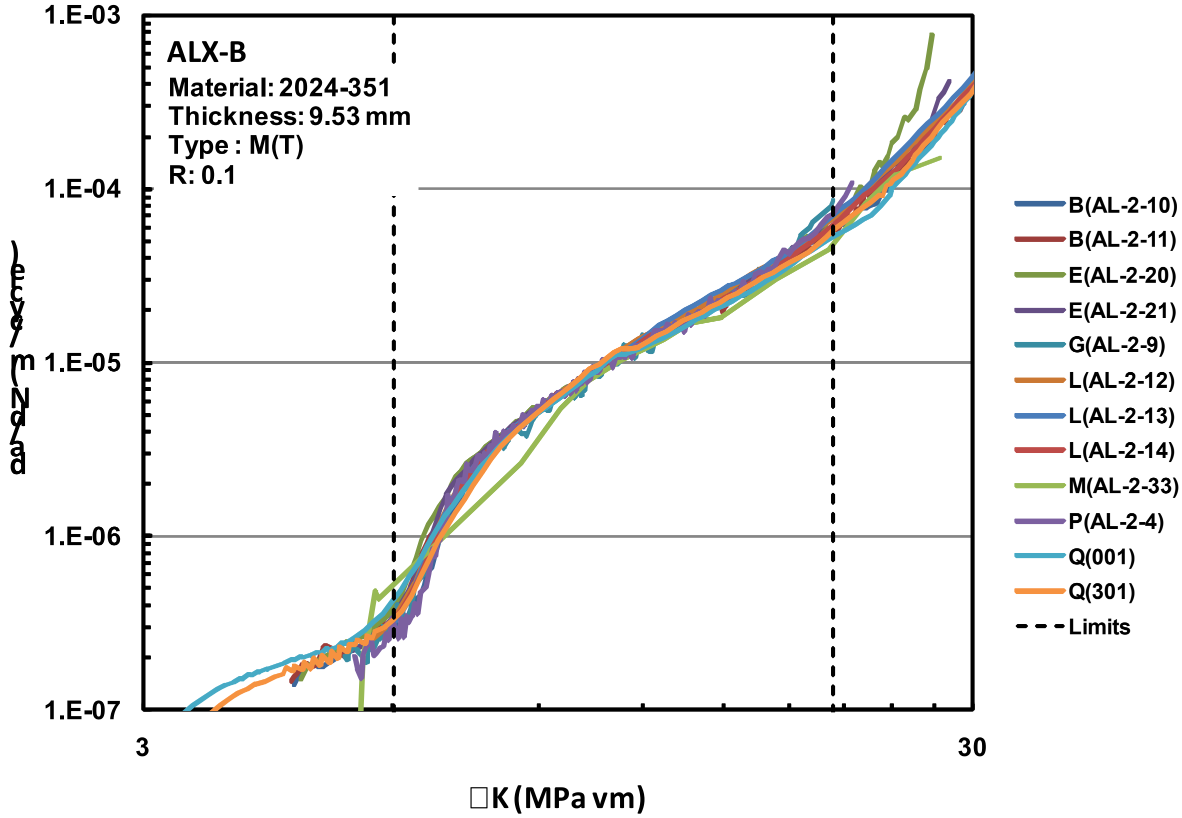


Figure 1: Crack growth rate versus ΔK: (E) ALX-B, 2024-T351, 9.53 mm thick, M(T) specimen, stress ratio 0.1.

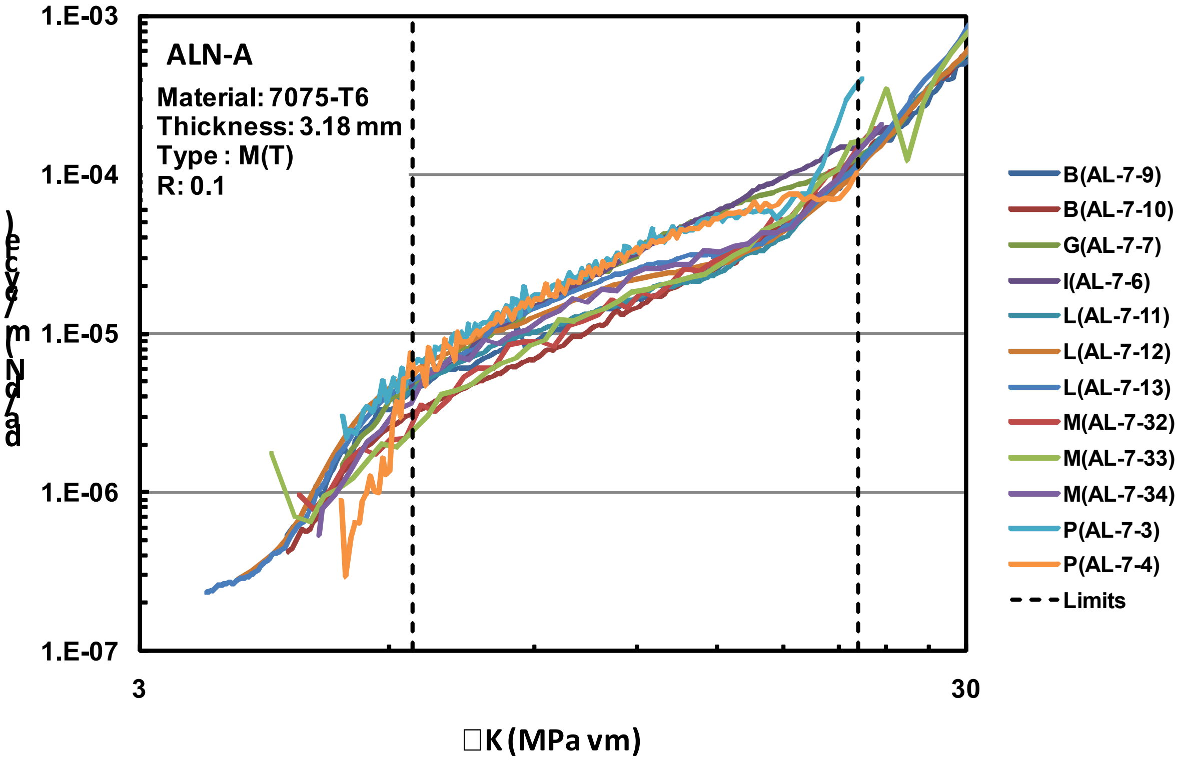


Figure 1: Crack growth rate versus ΔK: (F) ALN-A, 7075-T6, 3.18 mm thick, M(T) specimen, stress ratio 0.1.

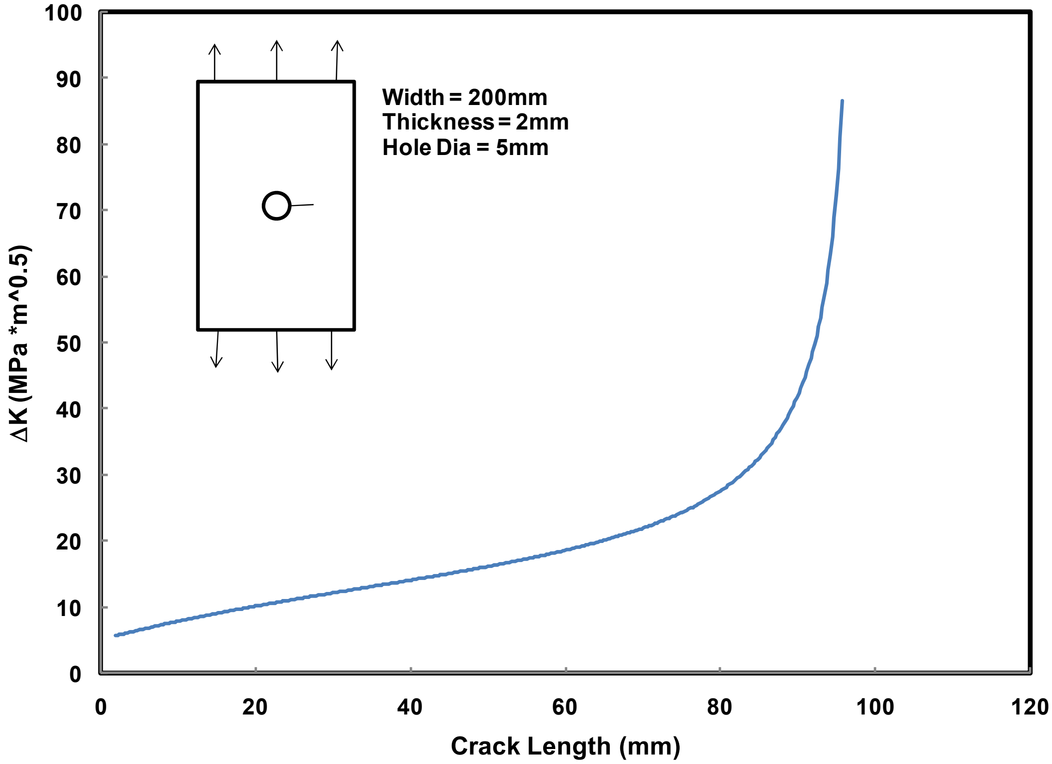


Figure 2: ΔK vs. a for a single through crack growing form a hole.

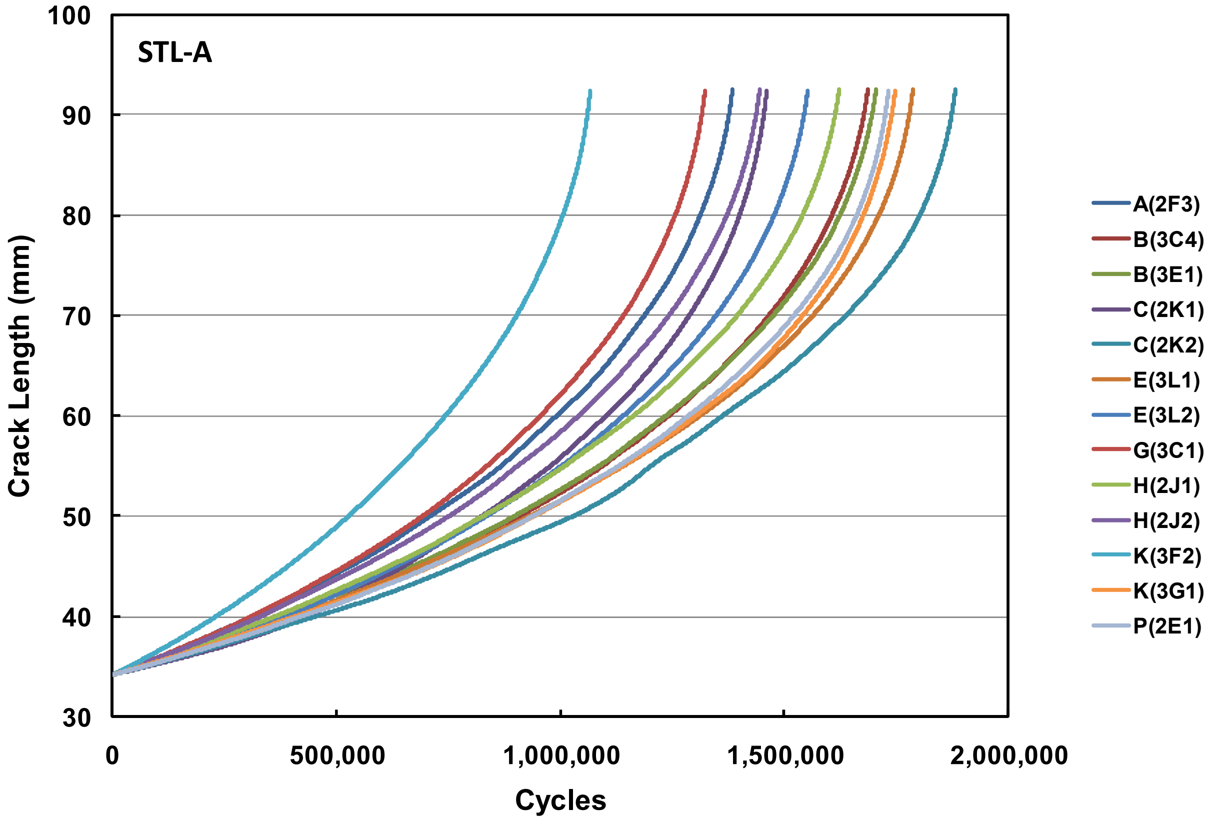


Figure 3: Crack length versus number of cycles for the specimens examined in this study; (A) STL-A, 4130 steel, 6.35 mm thick, C(T) specimen, stress ratio 0.1.

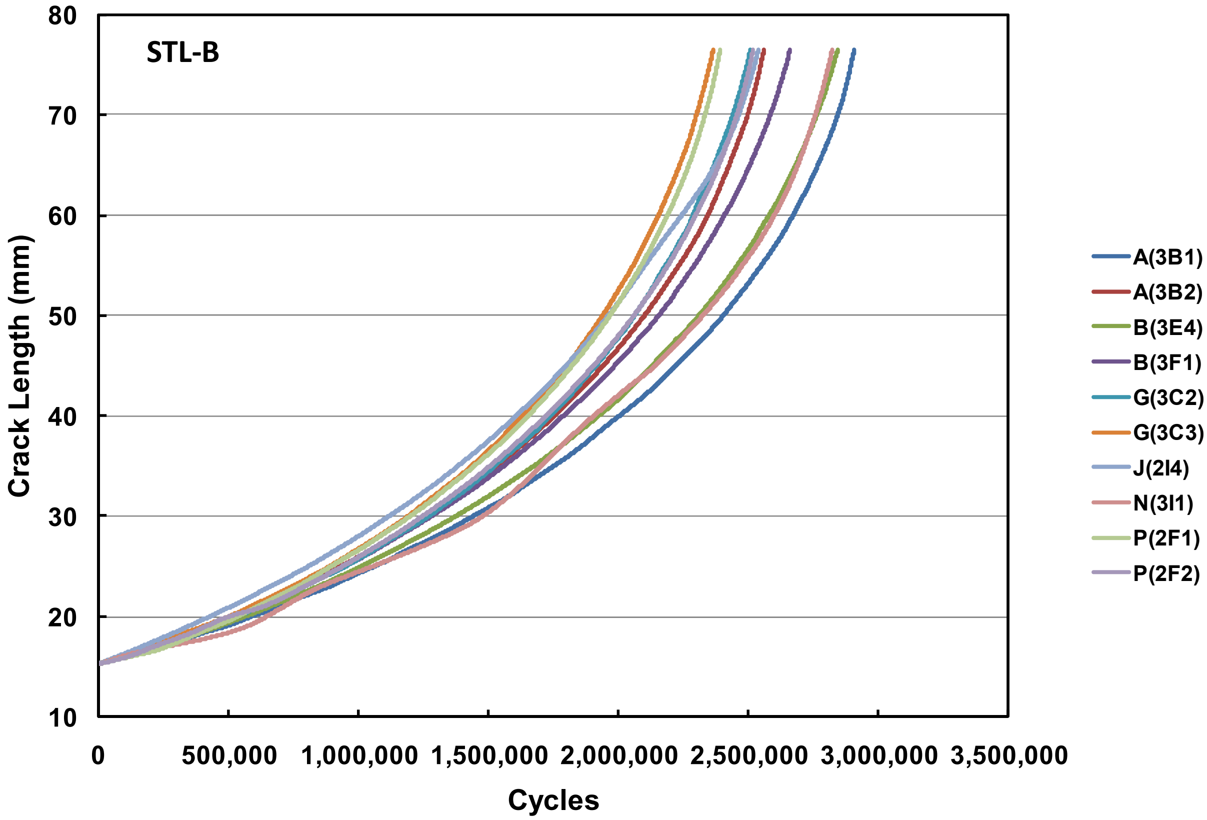


Figure 3: Crack length versus number of cycles for the specimens examined in this study; (B) STL-B, 4130 steel, 6.35 mm thick, C(T) specimen, stress ratio 0.8.

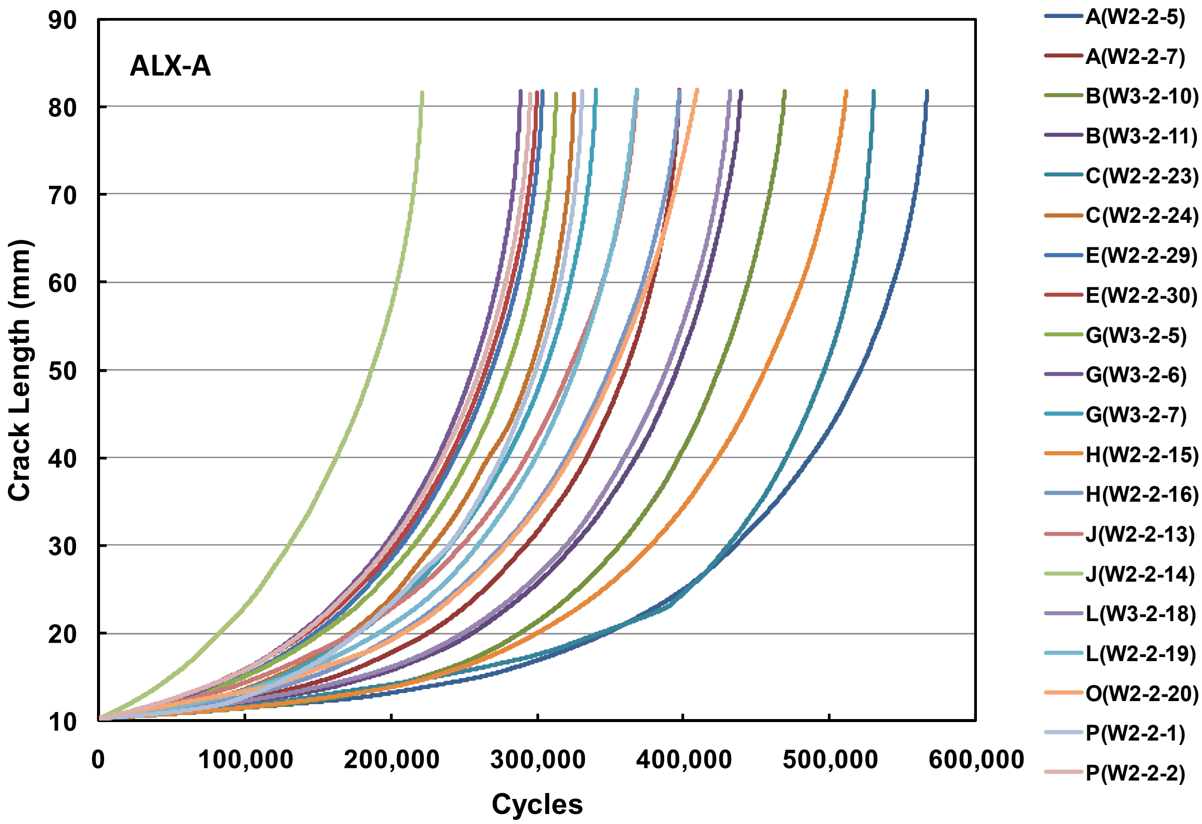


Figure 3: Crack length versus number of cycles for the specimens examined in this study; (C) ALX-A, 2024-T351, 6.35 mm thick, C(T) specimen, stress ratio 0.1.

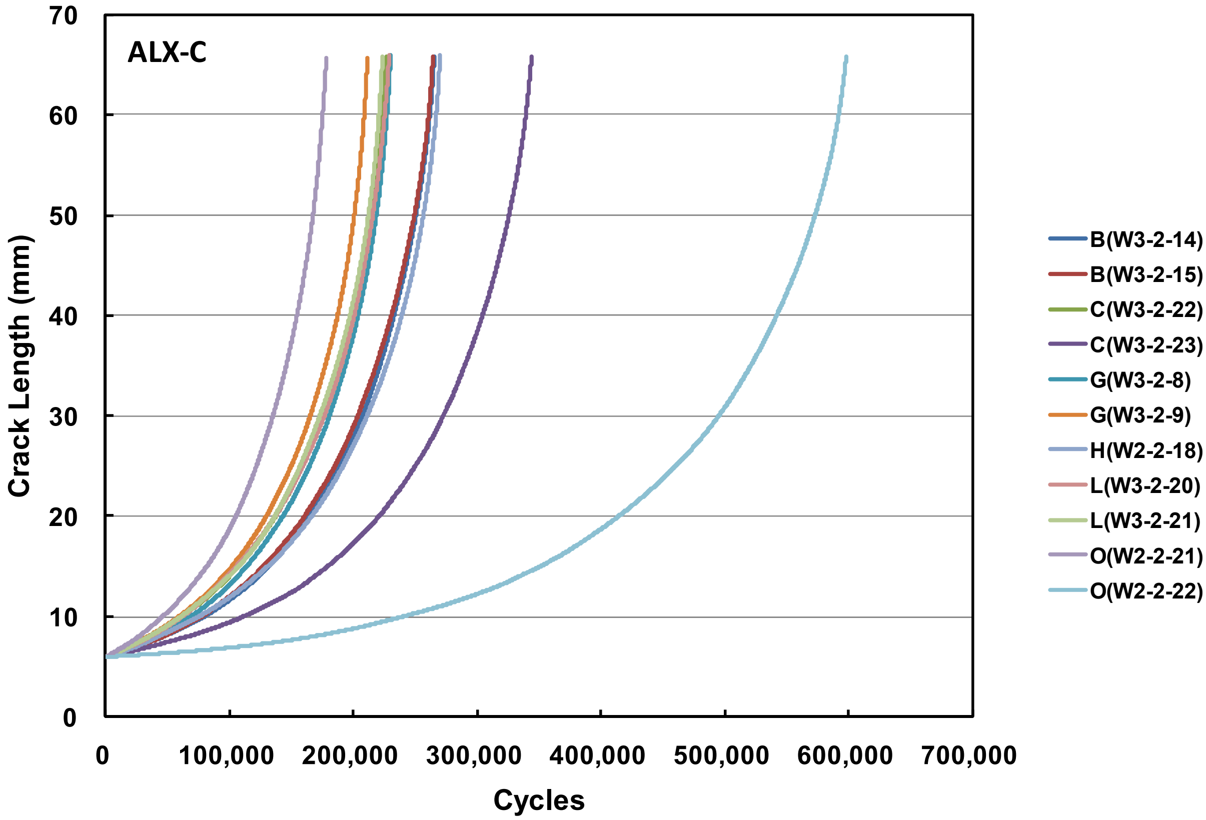


Figure 3: Crack length versus number of cycles for the specimens examined in this study; (D) ALX-C, 2024-T351, 6.35 mm thick, C(T) specimen, stress ratio 0.5.

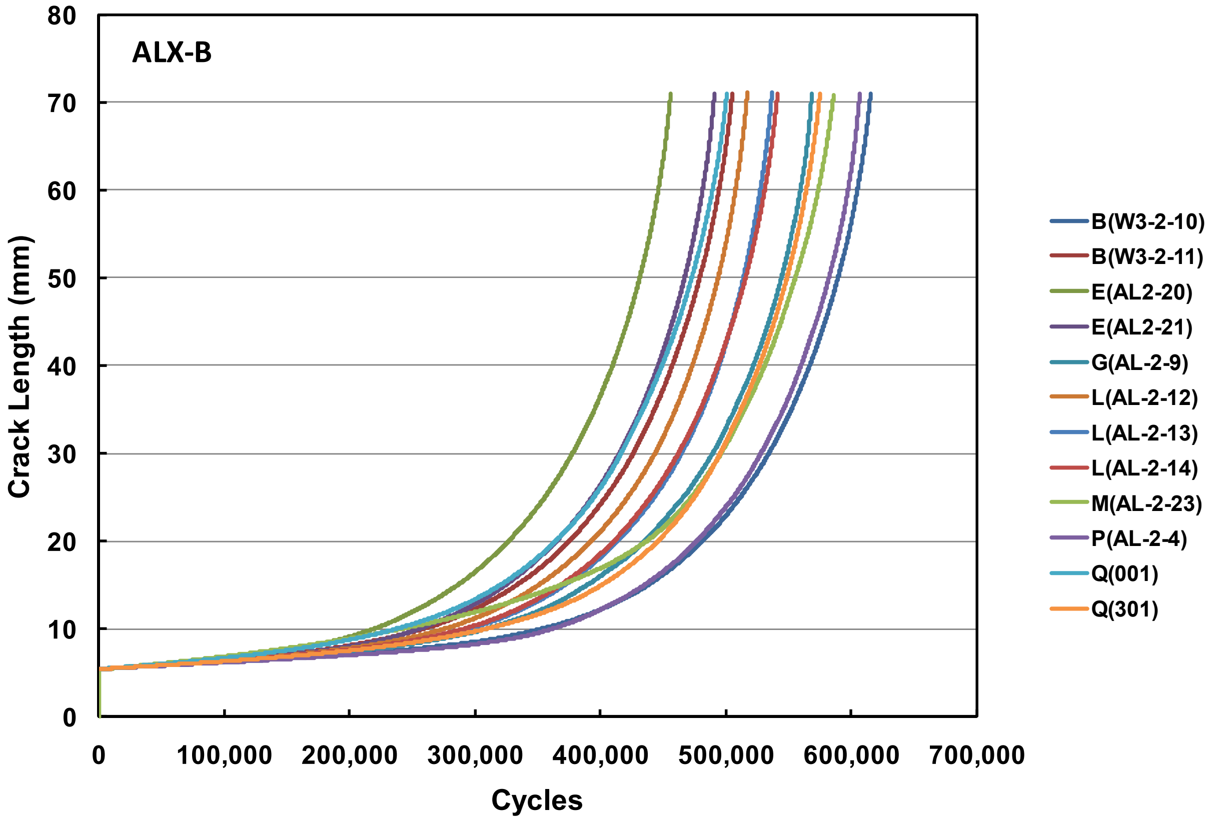


Figure 3: Crack length versus number of cycles for the specimens examined in this study; (E) ALX-B, 2024-T351, 9.53 mm thick, M(T) specimen, stress ratio 0.1.

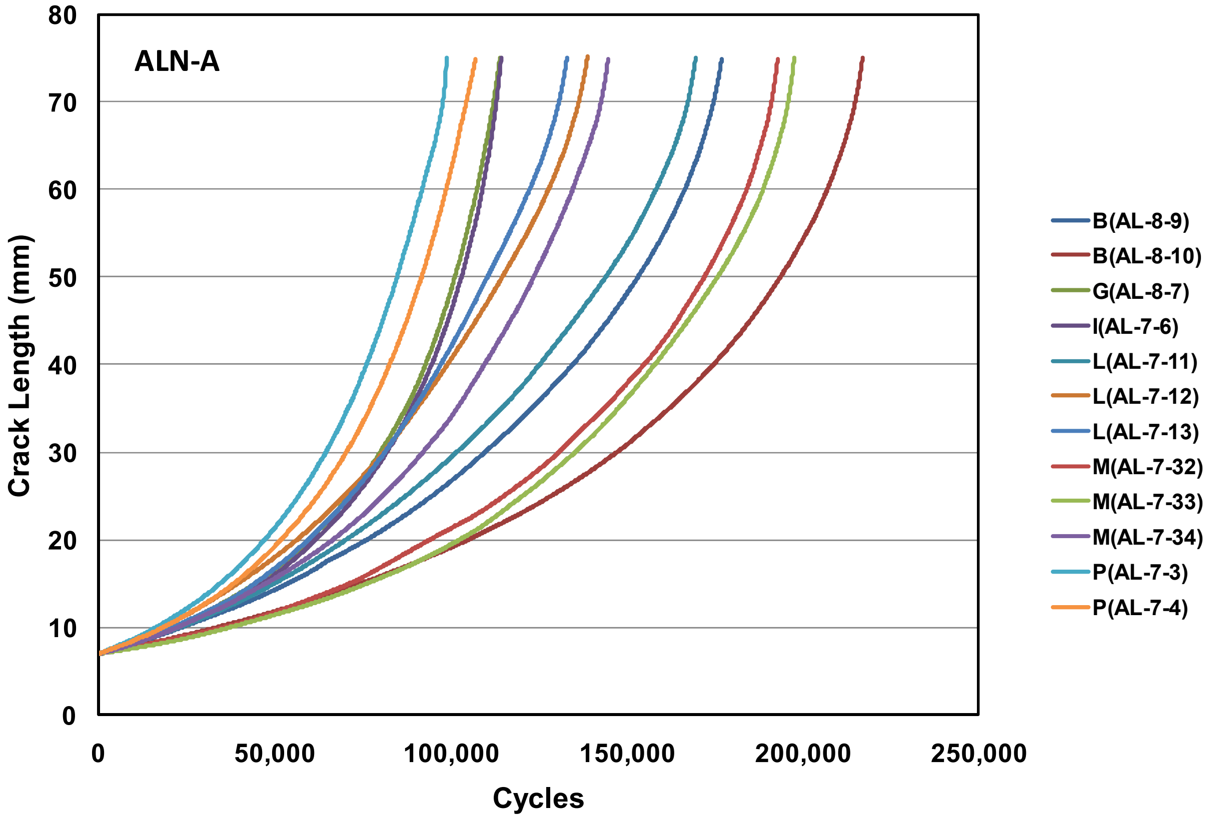


Figure 3: Crack length versus number of cycles for the specimens examined in this study; (F) ALN-A, 7075-T6, 3.18 mm thick, M(T) specimen, stress ratio 0.1.

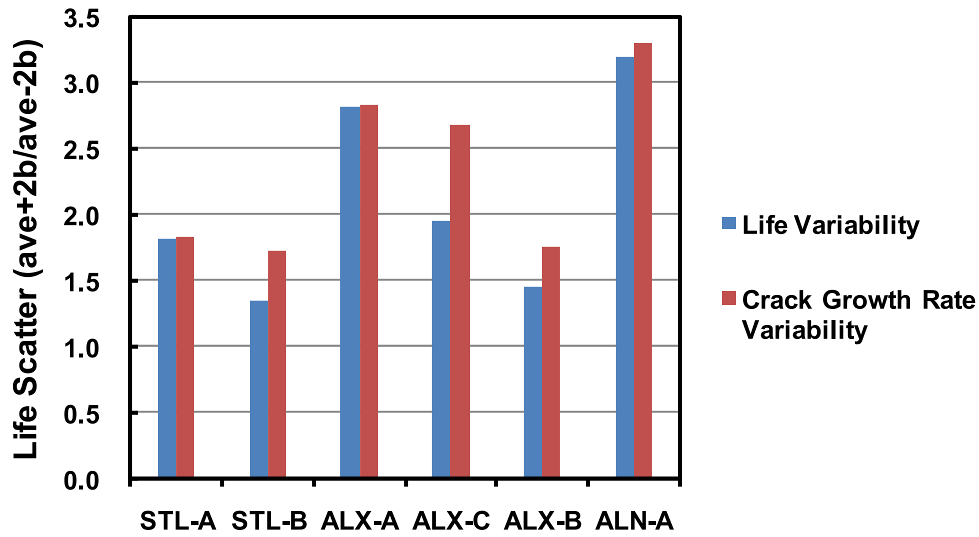


Figure 4: Comparison of the average crack growth rate variability and life variability for the six materials and test conditions (*ave* is the average life and *b* is standard deviation of that life distribution).

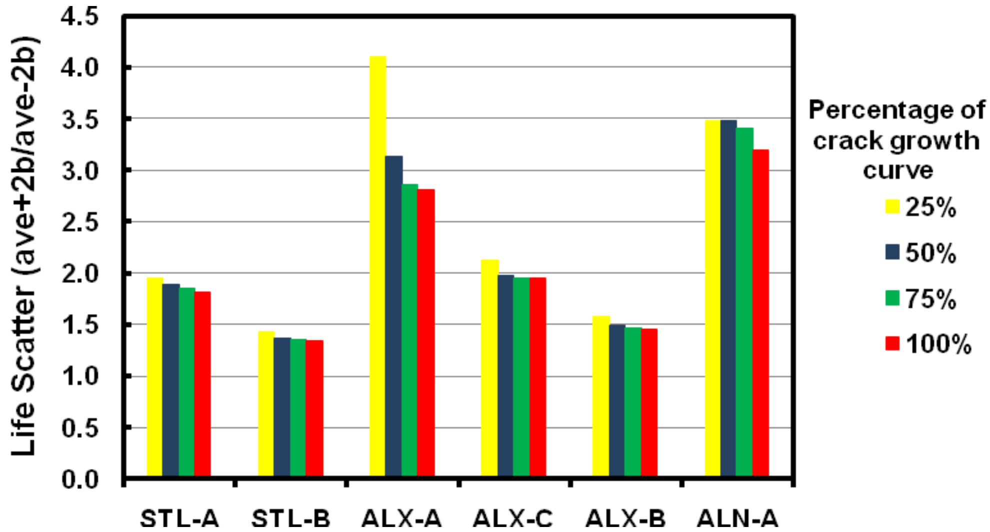


Figure 5: Comparison of the life variability for smaller fractions of crack extension for the six defferent materials / test conditions.